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Final report

Effects of Ice Accretion on Aircraft Aerodynamics

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Michael B. Bragg
University of Illinois at Urbana-Champaign

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Introduction

The primary objective of this research was to support the development of a new ice accretion model by improving our physical understanding of the ice accretion process through experimental measurements. The focus was on the effect of the initial ice roughness (smooth/rough boundary) on the accretion process. This includes understanding the boundary-layer development over the roughness and especially its effect on the heat transfer which is fundamental to the ice accretion process. The research focused on acquiring the experimental data needed to formulate a new ice accretion physical model.

Research was conducted to analyze boundary-layer data taken on a NACA 0012 airfoil ~~with roughness to simulate the smooth/rough boundary.~~ The effect of isolated roughness on boundary-layer transition was studied experimentally to determine if the classical critical roughness Reynolds number criteria could be applied to transition in the airfoil leading-edge area. The effect of simulated smooth/rough boundary roughness on convective heat transfer was studied to complete the study. During the course of this research the effect of free-stream wind tunnel turbulence on the boundary layer was measured. Since this quantity was not well known, research to accurately measure the wind tunnel turbulence in an icing cloud was undertaken. Preliminary results were attained and the final data were acquired, reduced and presented under a subsequent grant.

Results and Discussion

The research on the effect of simulated smooth/rough boundary roughness on boundary-layer transition was begun under an earlier NASA grant and completed during the initial stages of this grant. Detailed hot-wire boundary-layer profiles were taken on a NACA 0012 airfoil with and without simulated roughness. The data were analyzed to obtain boundary-layer velocity, turbulence intensity and turbulence intermittency profiles. The smooth/rough boundary was seen not to cause boundary-layer transition at the smooth/rough boundary location, but to initiate the transition process. The fully developed turbulent boundary layer was not present until the imposed pressure gradient became adverse. Kerho¹ presented a complete description of the experimental method and the results in his Ph.D. dissertation. Summaries of the results can be found in the papers by Kerho and Bragg^{2,3}.

Cummings completed his study of the effect of single, isolated roughness elements on boundary-layer transition on the NACA 0012 airfoil. A detailed review of this work may be found in his MS thesis.⁴ Cummings used hot-wire anemometry to determine the transition by measuring the turbulent intermittency in the wake emanating from the roughness element. He found that for roughness elements whose heights were less than the boundary-layer thickness and were positioned where the pressure gradient was adverse or only slightly favorable, transition did occur at approximately the classical

value of critical Reynolds number, $Re_k = 600$. Re_k values as high as 2000 were obtained in the leading-edge region in the favorable pressure gradient where the roughness elements were also higher than the local undisturbed boundary layer thickness. This work was summarized in Cummings and Bragg⁵

Heat-transfer measurements were made on the NACA 0012 airfoil downstream of the simulated smooth/rough boundary on the NACA 0012 airfoil. The same airfoil and roughness simulations were used as those of Kerho and Cummings described above. The heat-transfer measurements were made using an infrared spectroscopy method which was non-intrusive. The roughness caused increased heat transfer over the elements themselves, but the rates downstream were transitional and did not correspond to fully turbulent values. The elevated heat transfer was found to correlate well to regions in the flow where the measured turbulence intensity in the boundary layer at the wall increased. Details of this measurement technique and a thorough presentation of the results may be found in the MS thesis by Lee.⁶ A summary of early results may be found in Bragg, Lee and Henze.^{7,8}

During the boundary-layer measurements described above the turbulence level in the tunnel was artificially increased during some tests to evaluate the effect of values more similar to that experienced in icing wind tunnels. A sometimes significant effect of wind tunnel free-stream turbulence level on boundary-layer development was observed. However, the actual turbulence level in icing wind tunnels had only been measured without the spray on due to the lack of a proper diagnostic tool. During this research a hot-wire technique where water droplet strikes were digitally filtered out was developed to obtain the desired wind tunnel turbulence measurements. This technique and results for the NASA Lewis Icing Research Tunnel were reported by Bragg, Lee and Henze⁸ and Henze.⁹ Henze found turbulence levels in the IRT of 0.5 to 1.0%. The increase in turbulence due to the spray was almost entirely due to the air pressure used in the nozzles to atomize the water. The water pressure had essentially no effect on tunnel turbulence.

Summary

The research conducted under grant NAG3-1681 has been briefly reviewed in this report. A complete description of the research can be found in the many works cited. Any of these reports may be obtained from Prof. Bragg if needed.

References

- ¹ Kerho, M.F., "Effect of Large Distributed Roughness Near an Airfoil Leading Edge on Boundary-Layer Development and Transition", Ph.D. thesis, University of Illinois at Urbana-Champaign, 1995.
- ² Kerho, M.F. and Bragg, M.B., "Effect of Large Leading-Edge Roughness on Airfoil Boundary Layer Development", Paper No. 95-1803-CP, *Proceedings of the 13th AIAA Applied Aerodynamics Meeting*, San Diego, June 19-22, 1995, pp. 322-334.
- ³ Kerho, M.F. and Bragg, M.B., "Airfoil Boundary-Layer Development and Transition with Large Leading-Edge Roughness", *AIAA Journal*, Vol. 35, No. 1, 1997, pp. 75 - 84.
- ⁴ Cummings, M.J., "Airfoil Boundary-Layer Transition Due to Large Isolated 3-D Roughness Elements in a Favorable Pressure Gradient", M.S. thesis, University of Illinois at Urbana-Champaign, 1996.
- ⁵ Cummings, M.J. and Bragg, M.B., "Boundary-Layer Transition Due to Isolated 3-D Roughness on an Airfoil Leading Edge", *AIAA Journal*, Vol. 34, No. 9, 1996, pp. 1949 - 1952.
- ⁶ Lee, S., "Heat Transfer on an Airfoil with Large Distributed Leading-Edge Roughness," M.S. thesis, University of Illinois at Urbana-Champaign, 1997.
- ⁷ Bragg, M.B., Cummings, M.J., Lee, S. and C.M. Henze, "Boundary-Layer and Heat Transfer Measurements on an Airfoil With Simulated Ice Roughness", Paper No. 96-0866, AIAA 34th Aerospace Sciences Meeting, Reno, NV, January 15-18, 1996.
- ⁸ Bragg, M.B., Lee, S. and Henze, C.M., "Heat-Transfer and Freestream Turbulence Measurements for Improvement of the Ice Accretion Physical Model", AIAA Paper No. 97-0053, Reno, NV, January 6-9, 1997.
- ⁹ Henze, C.M., "Turbulence Intensity Measurements in Icing Cloud Conditions," M.S. thesis, University of Illinois at Urbana-Champaign, 1997.